Flexible Microstrip Antenna for Next-Generation Wearable Electronics

Synopsis of the Research Proposal

Submitted for the Registration in the

Ph.D. Programme (Part-time) in Engineering

By

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Under Supervision of

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Proposed Summary / Abstract

The rapid proliferation of wearable electronics has created a critical need for antennas that combine high electromagnetic performance with mechanical flexibility and user comfort. Traditional rigid antennas often suffer from performance degradation when placed on curved or dynamic surfaces, limiting their application in wearable devices, smart textiles, and Body Area Networks (BANs). This research focuses on the design, simulation, fabrication, and analysis of flexible microstrip patch antennas optimized for the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Key design considerations include substrate selection, patch geometry, feeding techniques, and mitigation of body-induced effects such as detuning and Specific Absorption Rate (SAR) constraints. Advanced flexible substrates such as polydimethylsiloxane (PDMS) and textile materials are employed to ensure mechanical conformability and biocompatibility while maintaining stable impedance, gain, and radiation patterns under bending and stretching conditions. The proposed methodology integrates electromagnetic simulation tools (HFSS, CST Microwave Studio) with iterative fabrication and testing, including wet etching and PCB prototyping, to validate performance in realistic on-body scenarios. This study also explores techniques for bandwidth enhancement, multiband operation, and radiation efficiency improvement**,** bridging the gap between theoretical antenna design and practical wearable applications. The research contributes to the development of miniaturized, high-performance, and safe wearable antennas, addressing contemporary challenges in healthcare monitoring, smart clothing, IoT devices, and wireless body-centric communication.

Keywords: Flexible Antenna, Microstrip Patch Antenna, Wearable Electronics, ISM Band, Substrate Selection, SAR, Body Area Network (BAN), PDMS, Textile Antenna, Electromagnetic Simulation, Radiation Efficiency, Multiband Operation.

1. Introduction to Antennas

Back in the 1890s, antennas were rare and mostly found in experimental setups used to prove that electromagnetic waves could actually travel through space. Fast forward to World War II, and antennas had become a household item, transforming everyday life through radio and later, television. At that point, nearly every home in the U.S. had at least one antenna growth on par with the rise of the automobile industry.

By the early 2000s, the number of antennas skyrocketed, mainly due to mobile phones. Today, the average person carries multiple antennas with them—inside their smartphone alone, you'll find antennas for Wi-Fi, GPS, cellular networks, Bluetooth, and sometimes even NFC. As wireless technology continues to weave itself into more aspects of life, this growth isn't slowing down anytime soon [1]-[2].

Moreover, the rapid rise of RFID technology means we may soon see antennas embedded in almost every item from products and packaging to pets, groceries, and toys. That could bring us to a point where there's nearly one antenna for every object on Earth a staggering leap from where we are now. So, understanding antennas, even just a little, is more important than ever. It gives insight into how the modern, connected world functions.

Now, while wireless communication is essential and often the only practical choice especially in mobile and remote scenarios there are still cases where wired connections are preferred. High-speed Ethernet for internet access or HDMI cables linking a gaming console to a TV, for example, are still the go-to for their stability and speed. But when mobility and convenience matter, antennas step in as the key enablers of wireless connectivity.

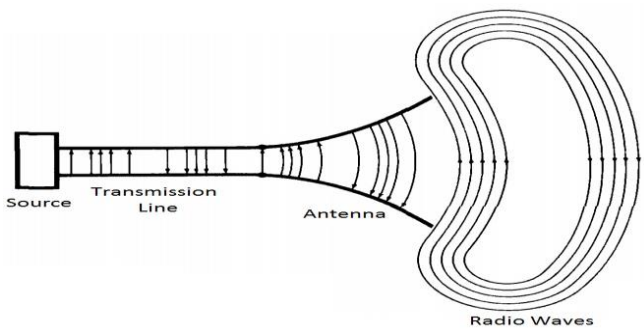

Fig.1. Antenna as transition device [3]

2. Fundamental Characteristics of Antennas

The comprehensive behavior and productivity of a wireless communication system heavily rely on the characteristics of the antenna it uses. For instance, the direction in which a system transmits or receives signals is directly tied to how the antenna radiates energy.

No matter where or how an antenna is used whether it's in a mobile phone, a satellite, or a Wi-Fi router it operates based on a set of core parameters. These are often referred to as the characteristics or properties of antennas, and understanding them is key to designing and using wireless systems effectively. Further the different parameters of antenna as given in [3]-[4] are categorized as:

- **Radiation Pattern**

Antennas don’t send signals equally in all directions. Instead, they radiate more energy in certain directions and less or almost none in others. This directional behavior is captured by what’s called the radiation pattern. It displays how the strength of the electromagnetic field fluctuates with direction, usually measured at a certain distance from the antenna. Field strength is expressed in volts per meter (V/m), and it's often visualized using 2D or 3D plots. If the plot shows just the directionality, it's called the Radiation Pattern. If it represents electric field strength, it's referred to as the Field Strength Pattern. When based on power per unit solid angle, it's termed as the Power Radiation Pattern.

- **Radiation Intensity**

This tells us how much power the antenna radiates in a particular direction. Unlike field strength, radiation intensity doesn’t change with distance. It’s measured in watts per steradian (W/sr) and is denoted by U.

- **Directivity and Gain**

The isotropic antenna is a theoretical benchmark in antenna engineering, representing an ideal source that radiates power uniformly in all directions. While this model is invaluable for theoretical comparisons, practical antennas inherently exhibit directional characteristics, concentrating radiation more prominently in certain directions. This directional tendency is quantitatively captured by the parameter known as directivity, which describes the ratio of an antenna’s radiation intensity in a specific direction to its average radiation intensity over all directions. In essence, directivity measures the degree to which an antenna focuses electromagnetic energy, providing critical insight into its radiation performance. Gain, on the

other hand, considers not just directionality but also efficiency it's a more practical version of directivity, including losses.

- **Radiation Efficiency and Power Gain**

Because real antennas are made of materials with resistance, some energy is lost as heat. Radiation efficiency quantifies the fraction of input power that is effectively converted into radiated electromagnetic energy, calculated as:

$$\eta_r = P_{rad} / P_{in}$$

Where:

P_{rad} = power radiated by the antenna

P_{in} = total power supplied to the antenna

- **Input Impedance**

To ensure efficient power transfer, the antenna's input impedance should match the impedance of the connected transmission line. A mismatch leads to signal reflections, reducing overall system performance and potentially causing long-term damage.

- **Effective Length**

This refers to the equivalent length of an ideal, straight-line antenna with uniform current distribution that would produce the same far-field radiation pattern as the actual antenna. It's a conceptual way to compare antennas based on how they radiate.

- **Bandwidth**

An antenna isn't always effective across all frequencies. Bandwidth refers to the range of frequencies over which the antenna maintains its key performance metrics like gain, input impedance, or VSWR (Voltage Standing Wave Ratio). Outside this range, the antenna's behavior may degrade.

- **Effective Aperture**

Primarily relevant for receiving antennas, effective aperture (or effective area) is a degree of how well the antenna captures energy from incoming electromagnetic waves. It's defined as the ratio of received power at the load to the power density of the incident wave.

- **Antenna Polarization**

Polarization refers to the orientation of the electric field of a transmitted electromagnetic wave. It can be linear (horizontal or vertical), circular, or elliptical. If no direction is specified, the polarization is assumed in the direction where the antenna provides maximum gain. Matching the polarization of the transmitting and receiving antennas is critical for effective communication.

3. Microstrip Patch Antennas

Microstrip patch antennas have become a popular and promising area of research in modern antenna technology. Their rising popularity is largely due to several advantages: they are lightweight, cost-effective, compact in size, low-profile, and relatively easy to manufacture. These characteristics make them ideal for integration into today's ever-shrinking and increasingly wireless electronic devices Recently, there has been an increasing focus on designing of microstrip antennas that support multiband and wideband operations. In order to eliminate the need for numerous different antennas for a variety of wireless applications, the objective is to create a single antenna that operates across multiple frequency bands. Numerous applications, such as biomedical telemetry systems, military systems, weather monitoring, and wireless communication technologies like Wi-Fi, heavily rely on microstrip patch antennas.

Three primary structural layers make up a microstrip patch antenna as shown in Figure 2. [5]-[6]

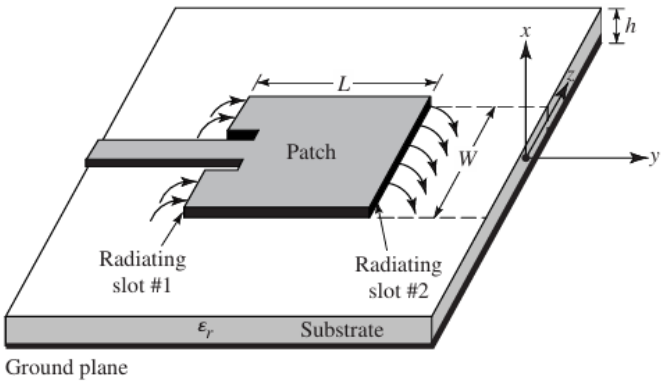

Figure 2: Microstrip antenna

- The radiating patch on top,
- A dielectric substrate in the middle, and
- A ground plane at the bottom.

The performance of the antenna is greatly influenced by the substrate, which is located between the patch and the ground plane. According to the intended use and performance requirements,

the patch is usually constructed of copper and can be shaped in a variety of ways, such as triangular, square, rectangular, circular or elliptical.

3.1 Antenna Design Equations and Fringing Effects

Fringing effects in microstrip patch antenna design describe to the extending of electric fields beyond the radiating patch's physical edges. This effect results from the patch's limited size, which hinders the total containment of electromagnetic fields beneath the conductor and is essential to the radiation mechanism of the antenna.

A number of structural factors influence the degree of fringing, chief among them the dielectric constant (εrεr) of the substrate material and the ratio of patch's length to the substrate height (L/hL/h) [7-8]. Since fringing effects have a direct impact on the effective electrical length of the patch and, consequently, the resonant frequency, impedance matching, and radiation characteristics of the antenna, precise modelling and compensation for them are crucial stages in the design process.

Fringing fields alter the resonance frequency by making the microstrip antenna appear to be electrically longer than its actual dimensions. Especially, the antenna resonates at a frequency that is somewhat lower than what its physical size would indicate. Because of this, fringing is essential for precisely forecasting antenna performance. To account for these effects in microstrip lines which are structurally similar a concept called the effective dielectric constant (ε_{reff}) is introduced. This value represents an average dielectric constant, acknowledging that the electromagnetic wave propagates partially in the substrate and partially in the air above it. The effective dielectric constant typically falls between 1 (air) and ε_r (substrate), and it shifts closer to ε_r as the operating frequency increases because more of the field becomes concentrated in the substrate. Overall, understanding and compensating for fringing effects is essential for the accurate design and modelling of microstrip patch antennas.

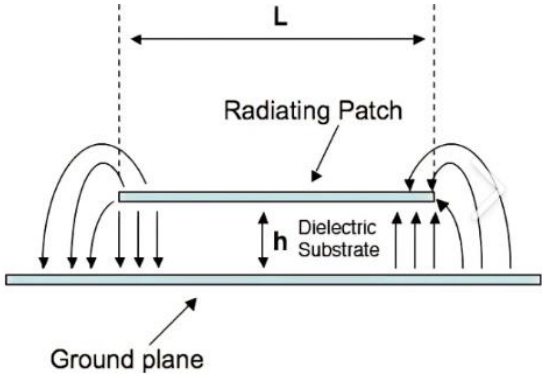

Figure 3 Fringing effects in microstrip patch antenna

The most critical step in antenna development is the finalization of design specifications, which are determined by the intended application. Antenna specifications are typically guided by system-level requirements, which are established through comprehensive analysis and simulation of the overall system such as a 5G network or a radar application by a system architect or engineer. These specifications are critically informed by the operational context; for instance, the performance criteria for a wireless mobile communication antenna differ substantially from those governing satellite or radar antenna systems, reflecting their distinct functional and environmental demands. Following are the design equations as described in [3] are depicted as follows:

1) Specify ε_r and h of substrate, the desired resonant frequency f_r, and the impedance Z_c, feed of the feeding transmission line.

2) Calculate width of patch using line.

$$W = \frac{2}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

(Selected to provide high radiation efficiency.) Ideally, the patch width (W) should be smaller than its length (L), i.e., W < L, to ensure operation in the fundamental TM010_{010}010 mode only. In practice, W > L may be employed if the patch is appropriately excited, so as to avoid excitation of higher-order modes (for example, the TM001_{001}001 mode becomes dominant when W > L). The width can be adjusted provided that the ratio W/L remains less than 2, in order to prevent a decrease in aperture efficiency.

3) Calculate

$$\varepsilon_{r,eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]$$

4) Calculate

$$\Delta L = 0.412h\,\frac{\left(\varepsilon_{r,eff} + 0.3\right)\left(\frac{W}{h} + 0.624\right)}{\left(\varepsilon_{r,eff} + 0.3\right)\left(\frac{W}{h} + 0.624\right)}$$

5) Calculate the effective length and guided wavelength λ.

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{r,eff}}} \quad \text{and } \lambda = 2L_{eff}$$

6) Calculate the patch length L (see below) and L/λ. Then, calculate and check that W/L < 2. If necessary, reduce W calculated in step 2 to be slightly less than 2L.

$$\text{L} = L_{eff} - 2\Delta L = \frac{\lambda}{2} - 2\Delta L$$

7) Calculate G1 ≈ G2 and B1 ≈ B2

$$G_{1,est} = \frac{W}{120\lambda_0}\left[1 - \frac{1}{24}(k_0 h)^2\right] \qquad \text{for } \frac{h}{\lambda 0} < \frac{1}{10}$$

$$B_{1,est} = \frac{W}{120\lambda_0}\left[1 - 0.636\,ln(k_0 h)\right] \qquad \text{for } \frac{h}{\lambda 0} < \frac{1}{10}$$

numerically integrate $G_1 = \frac{1}{\pi n_0}\left[\frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right]^2 \sin^3\Theta \, d\Theta$

$$B_1 = \left(\frac{G_1}{G_2}\right) B_{1,est}$$

where $k_0 = \frac{2\pi}{\lambda_0} = \frac{\omega}{c}$ is the free space wave number.

8) Calculate the characteristic impedance Zc, ant and admittance Yc, ant for the rectangular microstrip antenna.

$$Z_{c,ant} = \begin{cases} \frac{60}{\sqrt{\varepsilon_{r,eff}}} In\left[\frac{8h}{W}+\frac{W}{4h}\right] \\ \frac{n_0}{\sqrt{\varepsilon_{r,eff}}\left[\frac{W}{h}+1.393+0.667In\left(\frac{W}{h}+1.444\right)\right]} \end{cases} \qquad \frac{W}{h} > 1$$

And $Y_{c,ant} = \frac{1}{Z_{c,ant}}$

9) (Optional) Use Smith chart or direct calculation to verify

$$\widetilde{Y_2} = \widetilde{G_2} + j\widetilde{B_2} \approx G_1 - jB_1 = Y_1^*$$

10) Numerically calculate the mutual conductance between the slots

$$G_{12} = \frac{1}{\pi n_0}\int_{\theta=0}^{\pi}\left[\frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_{0(k_0 L\sin\theta)} sin^3\theta \, d\theta$$

11) Calculate Rin (used plus (+) sign in original equation).

$$Z_{in} = R_{in} = \frac{1}{2\,G_1 + G_2}$$

12) If an inset microstrip feed is required (i.e., Rin ≠ Zc, feed), calculate length y0 of the inset needed to match the rectangular patch to the feeding transmission line. When G1/Yc, feed << 1 and B1/Yc,feed << 1, a good starting point is

$$y_0 \approx \frac{L}{\pi}\cos^{-1}\left[\sqrt{\frac{Z_{c,feed}}{R_{in}}}\right]$$

This answer can be checked using

$$R_{in}(y_0) = \frac{1}{2\,G_1 + G_2}\left[\cos\theta\left(\frac{\pi y_0}{L}\right) + \frac{G_1^2 + B_1^2}{Y_{c,feed}}\sin\theta\left(\frac{\pi y_0}{L}\right) - \frac{B_1}{Y_{c,feed}}\sin\left(\frac{2\pi y_0}{L}\right)\right]$$

If Rin(y_0) is not equal to Z_c, feed, the length y_0 should be iteratively adjusted until Rin (y_0) = Z_c, feed.

13) Determine the width W0 of the feeding microstrip transmission line.

3.2 Criteria for Substrate Selection in Microstrip Antennas

In microstrip antenna design, the substrate plays a crucial role not only by providing mechanical support to the antenna structure but also by influencing its electrical performance as mention in [9]. Since the substrate lies between the radiating patch and the ground plane, its material properties directly affect parameters like impedance, bandwidth, efficiency, and radiation characteristics. Choosing the right substrate involves balancing several key considerations. One of the major factors is surface wave excitation, which occurs more prominently when using substrates with higher dielectric constants and greater thicknesses. These surface waves can lead to energy loss, reduced efficiency, and unwanted radiation especially between elements in antenna arrays. Substrate with optimal thickness and low dielectric constants are typically chosen to reduce such problems. The ideal substrate thickness should be in range of $0.01\lambda_o$ to $0.05\lambda_o$ which is considered to supress multiple surface wave modes.

The need for antennas that are not only functional but also flexible enough to accommodate curved and dynamic surfaces has increased due to the increasing integration of technology into daily life. In order to retain consistent electromagnetic performance, including impedance matching, gain, radiation patterns and efficiency, flexible and conformal antennas are designed to twist, blend and conform to non-planar surfaces. Because of these characteristics, they are especially well-suited for wearable electronics and gadgets that are affixed to moving body parts. For example, a health-monitoring patch can naturally adapt to a user's movements while maintaining stable communication links. By merging mechanical flexibility with strong electromagnetic properties, such designs improve user comfort, enhance versatility, and allow seamless integration in situations where conventional rigid antennas would be unsuitable or hinder performance.

Wearable variants in comparison to conventional antennas should operate reliably in highly dynamic environments. They frequently come into contact with biological tissues and are subjected to mechanical forces such as bending, twisting, and stretching. Since the human body is made up of tissues with high dielectric constants and strong electrical, the close proximity to the body poses significant operational obstacles. In order to preserve performance and guarantee user safety, careful design is required since electromagnetic energy absorption by these tissues can raise the Specific Absorption Rate (SAR), cause frequency detuning, and decrease radiation efficiency. Another crucial component of wearable antenna design is substrate selection. Impedance matching and radiation stability can be greatly impacted by frequency dispersion, which occurs when a substrate's dielectric constant and loss tangent

change with frequency, particularly over large bandwidths. Therefore, to reduce dielectric losses and attain high efficiency, especially at high frequencies, substrates with low loss tangents are desired. Conductor losses, thermal stability, mechanical flexibility, machinability, solderability, weight, durability, and cost must all be evaluated for practical design. While common materials like FR4 are inexpensive and suitable for frequencies above 1 GHz, their limitations make them unsuitable for high-precision or wearable applications.

Advanced flexible substrates have attracted considerable research attention. Polydimethylsiloxane (PDMS), an elastomeric polymer, offers biocompatibility, chemical inertness, and mechanical flexibility. Its low elastic modulus (1–3 MPa versus ~50 GPa for glass) allows conformal integration, while excellent thermal and electrical insulation protects embedded components over a wide temperature range (−50 °C to 200 °C). With a relatively stable dielectric constant ($\varepsilon_r \approx 2.3–2.8$) and easy fabrication via replica molding, PDMS is ideal for flexible RF applications. Textile substrates, such as denim, also provide promising options for wearable antennas. Successful implementation requires precise characterization of the fabric's electromagnetic properties, typically using a dielectric probe kit to measure the reflection coefficient. Accurate dielectric data enable the design of antennas that can be integrated into clothing without compromising communication performance, ensuring both functionality and user comfort.

4. Statement of Proposal

4.1 Problem statement:

Antennas with great electrical efficiency and mechanical flexibility are desperately needed as wearable electronics become more and more integrated into fitness tracking, helath monitoring, and smart textiles. This will provide for seamless integration into clothing or direct placement on the body. An essential frequency for many of these wearable devices is the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, which is extensively used for Bluetooth and Wi-Fi communications. Due to their incapacity to adapt to curved or dynamic surfaces, conventional rigid antennas are insufficient and frequently experience performance degradation while in operation. A viable substitute that offers greater comfort and adaptability is made of flexible materials like fabrics and polymers.

Antenna designs must deal with problems such frequency detuning from body proximity, decreased radiation efficiency, and unstable impedance matching. Furthermore, in order to guarantee user safety without sacrificing wireless reliability, adherence to safety regulations-specifically, Specific Absorption Rate (SAR) limits-is crucial. The research

overcomes the complex issues by creating and testing wearable antennas that operate in the 2.4 GHz ISM band and are made on textile or polymer substrates. To close the gap between theoretical design and real-world usability, a major emphasis is made on attaining and sustaining stable electromagnetic performance under realistic circumstances, such as bending deformation and on-body operation.

4.2 Background

Developments in wireless technologies have had a significant impact on wearable antennas, particularly in fields like smart textiles, military communications, fitness tracking, and healthcare monitoring. These applications form part of wireless Body Area Networks (WBANs) [10]. In contrast to traditional antennas, wearable versions need to function consistently in extremely demanding and dynamic setting. They frequently come into contact with biological tissues and are subjected to mechanical forces such bending, twisting, and stretching. One major operational problem is the intimate closeness of wearable antennas to the human body. In order to preserve performance and user safety, careful design considerations are required because the absorption of electromagnetic energy by bodily tissues can increase the Specific Absorption Rate (SAR), cause frequency detuning, and decrease radiation efficiency. Together, these elements highlight the necessity of specific design methodologies to guarantee wearable antenna system's functionality and user safety. SAR must stay below regulation levels in order to adhere to international safety standards (e.g., <1.6 W/kg as per FCC, <2 W/kg as per ICNIRP).

Researchers have concentrated on creating flexible antennas out of textile, polymer, or composite materials in order to overcome these obstacles. These materials allow the antennas to be easily incorporated into clothing or applied directly to the skin in addition to providing mechanical comfort and conformability. However, these substrates flexibility can change the antenna's resonance frequency, bandwidth, and impedance matching, particularly when it is bent or stretched. The behavior of the antenna is greatly influenced by important material characteristics as relative permittivity (ε_r), loss tangent (tan δ), conductivity (σ), and mechanical elasticity. For example, strong conductivity in the radiating elements guarantees low resistive losses, while a low loss tangent increases radiation efficiency. Common materials used include polyimides, latex, polyester fabrics, and silver-coated textiles, each selected based on a trade-off between electromagnetic performance and mechanical flexibility.

In addition to material challenges, wearable antennas face significant electromagnetic coupling with the body, which can compromise performance and pose safety concerns. To mitigate these issues, researchers have introduced periodic electromagnetic structures such as [11]-[12]:

- **Artificial Magnetic Conductors (AMCs):** Engineered surfaces that mimic Perfect Magnetic Conductors (PMCs), providing in-phase reflection and reducing backward radiation toward the body.
- **Electromagnetic Bandgap (EBG) structures:** Periodic arrangements that create a frequency band where surface waves cannot propagate, thus minimizing surface current losses and body interference.
- **High Impedance Surfaces (HIS):** Surfaces that inhibit wave propagation and reduce SAR, often realized using patch arrays with vias connecting to a ground plane.
- **Metamaterials (MTMs):** Artificial materials with negative refractive index or other exotic properties that enhance gain, directivity, and bandwidth.
- **Metasurface:** 2D planar counterparts of metamaterials used to control electromagnetic wavefronts with high precision.

These structures serve as effective isolation barriers between the radiating element and the human body, yielding significant improvements in key performance metrics such as front-to-back ratio (FBR), gain, and impedance bandwidth, while simultaneously reducing Specific Absorption Rate (SAR) [13]. Critically, they enable this enhancement without compromising the low-profile, and compact form for user comfort and practical wearability.

Nevertheless, the development of antennas capable of maintaining stable electrical performance under real-world conditions—such as body movement, textile deformation, or moisture exposure—remains a substantial engineering challenge. Rigorous validation through phantom body modeling, mechanical bending tests, SAR compliance analysis, and empirical on-body measurements is therefore indispensable to transition these designs from laboratory prototypes to functional, reliable devices.

In summary, the field of flexible and wearable antennas continues to evolve rapidly through innovations in materials, electromagnetic design, and fabrication techniques. However, the principal challenge persists: achieving a harmonious balance between robustness, safety, high performance, and adaptability to the dynamic human environment. Addressing these multifaceted demands will require sustained interdisciplinary collaboration to pave the way for

next-generation wearable systems in healthcare, defense, and consumer electronics.**4. Motivation and Need for the Research**

Despite significant advancements in the development of wearable antennas, a considerable number of current designs demonstrate limitations when deployed in real-world operating environments. Antennas integrated onto the human body are subjected to extreme and dynamic conditions—including persistent mechanical deformation, moisture, temperature fluctuations, and variable skin contact. However, validation for many reported prototypes remains confined to idealized laboratory settings, revealing a critical disconnect between simulated performance and practical usability. Furthermore, the successful integration of these antennas into garments or directly onto the skin introduces a complex set of design constraints that extend far traditional electromagnetic metrics. Challenges such as ergonomic comfort, mechanical resilience, biocompatibility, and cost-effective manufacturing are frequently unheeded in research, despite being indispensable for widespread commercial viability. This underscores the necessity for novel, interdisciplinary design philosophies that harmonize electrical performance with human-centric functionality.

An additional layer of complexity arises from stringent regulatory and safety mandates, particularly those governing the Specific Absorption Rate (SAR). So, the task of designing antennas that simultaneously achieve high radiation efficiency and low SAR values is not merely a technical obstacle but a public health imperative.

Furthermore, the evolving demands of body-area networks for applications in continuous healthcare monitoring, smart textiles, and tactical gear require antennas that are multiband, miniaturized, highly conformal, and electromagnetically stable across diverse scenarios. Many contemporary designs resort to compromising one key performance indicator to enhance another, highlighting a persistent lack of optimally balanced solutions in the current literature. This indicates a clear need for more sophisticated co-design approaches capable of managing these competing trade-offs effectively.

Thus, the motivation for this research driven by following reasons:

- Improve the electromagnetic performance of wearable antennas without compromising on comfort or flexibility.
- Minimize radiation exposure risks by reducing SAR through smart material selection and periodic structure integration.

- Design mechanically robust antennas that retain performance under realistic operating conditions.
- Provide new insights into WBANs, e-textiles, and body-centric communication systems by proposing innovative and practical antenna solutions.

5. Literature Review

Paper [14] presents a wearable antenna capable of both wireless communication and real-time breath detection. Using composite metal-glass-polymer fibers, the design ensures comfort, flexibility, and environmental shielding while maintaining good RF performance.

The authors in [15] present a low-profile, pentagonal-shaped monopole antenna tailored for wearable applications. The design emphasizes miniaturization and ultrawideband (UWB) performance, effective in both free space and body-worn conditions. It incorporates a pentagonal radiator, a 50-ohm matched feed, and square slots on a defected ground structure fabricated on a 15 mm × 25 mm FR4 substrate, achieving UWB performance from 2.9 GHz to 11 GHz. The measured gains at key frequencies are −0.81, −2.81, −1.16, and 2.83 dBi.

In [3], the authors discuss recent advancements in materials for wearable antennas, such as conductive textiles, flexible polymers, graphene, and metamaterials, enhancing flexibility and integration. They also review fabrication techniques like inkjet and screen printing, 3D printing, polymer embedding, microfluidic channels, and fabric embroidery, detailing material considerations and antenna characteristics.

The study in [16] introduces a wearable PIFA antenna with an all-textile metasurface, showing a peak gain of 6.70 dBi, average efficiency of 77%, and operating range from 4.96 to 5.90 GHz, suitable for 5 GHz WBAN applications. Performance comparisons with existing solutions highlight its bandwidth, efficiency, and wearability.

In [17], the authors propose a compact, dual-mode, pattern-reconfigurable wearable antenna for 2.4-GHz WBAN. The antenna covers 3.8% bandwidth in the 2.4 GHz ISM band and maintains stable performance across different body placements.

The research in [15] explores seamless integration of wearable microstrip patch antennas into healthcare systems, discussing interfacing with monitoring devices, data storage, and transmission. It emphasizes miniaturization, multiband operation, and bandwidth enhancement.

In [18], a multiband microstrip patch antenna is optimized using a nature-inspired algorithm for RF energy harvesting. Operating in LoRa WAN and cellular bands (GSM-1800 and UMTS), it offers a gain of 3.94 dBi with broadside radiation and multiband capabilities.

The beveled Y-shaped monopole antenna in [19] spans 3.1–10.6 GHz and includes a fork-slotted EBG structure on the same plane. With a compact 8 × 8 mm^2 form factor, it achieves 6.25 dBi peak gain and demonstrates high radiation efficiency.

In [20], a dual-band wearable antenna operates at 2.45 GHz and 5.5 GHz, with a compact size of 44.1 × 44.1 mm^2. It delivers −0.67 dBi gain in free space, increasing to 7.4 dBi off-body, with 9% power loss when body-worn.

Paper [21] proposes a 5 GHz wearable antenna array for WBANs, achieving circular polarization and wide bandwidth. It offers 43% impedance bandwidth, 60° beamwidth, and 34% AR bandwidth using textile materials for flexibility.

An ultra-compact implantable antenna in [22] operates in ISM bands with 29% bandwidth and -24 dBi gain, tested in multilayer tissues up to 29 mm depth. Made of RO3003 substrate and ceramic coating, it complies with IEEE/ICNRP SAR limits.

In [23], a flexible UWB antenna with a hexagonal patch and flowerbud-like cuts is presented on a low-dielectric foam substrate ($\varepsilon r = 1.07$), measuring 38 × 30 × 1.7 mm^3. It achieves a fractional bandwidth of 125.17% with 5.24 dB total gain.

The design in [24] operates at 2.45 and 5.8 GHz, commonly used for IoT and wireless communications. It demonstrates high radiation efficiency (>90%) with 1.03 dB and 4.29 dB peak gain at respective bands.

Authors in [25] address low-efficiency challenges in small antennas using fractals, metamaterials, and active techniques. A wideband passive/active antenna for 1.25–3.25 GHz achieves over 12 dB gain with a noise figure of 0.6 dB.

Paper [26] investigates the role of electro-textile and polyester material properties on performance and detuning of a DGS-based wearable antenna. The study also emphasizes manufacturability and large-scale integration.

The folded-ring dual-band antenna in [27] is designed for 2.45 GHz and 3.45 GHz off-body communication. With a rigid-radiator and textile-based ground, it delivers 5.1 and 8.6 dB gain and over 90% efficiency on human phantom models.

Paper [28] highlights a dual-mode antenna reconfigurable via p-i-n diodes covering the 2.4 GHz ISM band. While the 3.8% overlapped bandwidth is demonstrated, further analysis on switching speed and power efficiency is suggested.

In [29], the study emphasizes antenna robustness under bending and crumpling. With 24.4% bandwidth, 10.59 dBi gain, and a compact footprint, the design suppresses cross-polarization and retains high performance under deformation.

Research in [30] explores the impact of real-world environments and SAR variation on antenna behavior. The design shows 3.74 dBi and 5.13 dBi gain at 2.4 and 5.8 GHz with over 90% efficiency and diverse radiation patterns.

Paper [31] proposes a 1.575 GHz textile GPS antenna with DGS to mitigate detuning from bending. The flexible design stabilizes operating frequency despite structural deformations.

The jute textile antenna in [32] is designed for direct skin contact and performs reliably even in the presence of sweat. It is robust under physiological stress, supporting wearable applications.

Further in [33], the jute-based antenna shows resilience to different absorbency levels and bending, though research gaps include long-term durability and material degradation.

In [34], a compact 14 × 23 mm² antenna operates at 4.5 GHz (sub-6 GHz 5G) with 0.41 W/kg SAR. Fabricated on chitosan, it is sustainable and plastic-free, ideal for Internet of Healthcare Things (IoHT).

Paper [35] introduces an intraoral tongue drive system (iTDS) antenna for assistive applications. It preserves tongue mobility and is optimized for buccal shelf installation, offering improved control for disabled users.

The study in [36] evaluates a felt-based cloth antenna with a background plane, using Aaronia-shield conductive fabric. Performance is analyzed in free space and near-body conditions, including relative humidity impact.

In [37], a cloth-based C-shaped antenna for IoT is introduced. Though initially unstable, the use of AMC structures compensates for body proximity losses. However, its performance degrades on the chest.

Using CST, [38] simulates a smart watch strap antenna on a flexible Roger 3003C substrate. At 2.45 and 5.8 GHz, it achieves gains of 2.44 dB (via a unit cell reflector) with up to 95% efficiency.

Paper [39] explores PET, PTFE, Teflon, and PVC substrates for 2.45, 4.45, and 7.25 GHz antennas. It evaluates flexibility, shape retention, and bending tolerance for general IoT wearable uses.

A tri-band PET-based patch antenna in [40] (5.8, 6.2, 8.4 GHz) shows conformal performance and acceptable SAR, suited for on-body wearable systems with flexible, curved surfaces.

In [41], a high-performance folded-ring dual-band antenna is validated for off-body use. Gaps remain in long-term durability, movement-based testing, and clothing interaction studies.

6. Research Gaps:

- **Miniaturization and Compactness**

Miniaturization focuses on the size of antennas or related components without compromising their performance. The idea is to create smaller designs that still deliver the same or even better functionality. This is especially important for applications where space is finite, like in smartphones, wearable devices, IoT sensors, or medical implants. Achieving compactness doesn't just mean making things smaller it also means using the available space more efficiently. As technology advances, new materials, improved manufacturing techniques, and smarter design strategies are making it possible to build powerful antennas in tighter, more confined spaces.

- **Flexible and Conformal Design**

The growing integration of technology into daily life has driven the demand for antennas that not only function effectively but also adapt to dynamic and curved surfaces. In order to retain consistent electromagnetic performance, including impedance matching, radiation patterns, gain, and efficiency, flexible and conformal antennas are designed to blend, twist, and conform to non-planar surfaces. Because of these characteristics, they are especially well-suited for wearable electronics and gadgets that are attached to moving body parts. A health-monitoring patch, for example, can adapt to a user's movements naturally while maintaining dependable communication connections. These designs provide solutions in situations where conventional

rigid antennas would be unfeasible or sacrifice performance by fusing mechanical flexibility with strong electromagnetic properties. They also improve user comfort, boost versatility, and facilitate seamless integration.

7. Research Objectives:

- The primary aim of this research is to conceptualize, fabricate, and computationally model a new flexible antenna structure which has been particularly tailored for the stability of operation within the ISM frequency ranges. The design approach will consider some of the most important parameters of performance that are significant to contemporary applications, i.e., compactness to fit seamlessly, mechanical flexibility to enable fitting onto non-planar surfaces, and radiation performance stability under bending conditions. The objective is to provide a consistent and high-efficiency antenna solution that is most appropriately tailored to the critical demands of wearable technology and other conformal electronic devices.
- To fabricate the proposed antenna design using suitable flexible substrates ensuring practical realization of the simulated model.
- To experimentally validate the simulated performance of the antenna through comprehensive measurements of the fabricated prototype, and to analyze the consistency between simulated and measured results.

8. Research Methodology:

This work is designed to achieve a novel flexible based microstrip patch antenna for on body wearable applications with enhanced gain, bandwidth, radiation efficiency, return loss and VSWR. The designed antenna is intended for ISM-band applications and focuses on substrate selection and microstrip line feeding in order to obtain good performance as well as for the user comfort.

Simulations are performed in Ansys HFSS and CST Microwave Studio based on the comprehensive models of the wearable system, lossy substrate, and human body effects, and provide accurate prediction of the impedance matching, radiation patterns and the whole antenna efficiency. Post-optimisation, a prototype will be fabricated with an economical and flexible material; its performance is confirmed by means of intensive tests. This reiterative design, simulation, fabrication and testing that targets issues such as operating at multiple bands, miniaturization and human body interactions, provides the missing link between design at theory and practical implementation, achieving a high performance, wearable antenna for real-world applications.

EM Simulation and Optimization:

Utilize electromagnetic (EM) simulation software in particular CST Microwave Studio, HFSS, or FEKO to model and simulate the patch antenna design. Set up the simulation with the chosen substrate material, dimensions, feeding method, and other parameters. To evaluate and enhance the antenna's performance, simulations will be performed focusing on parameters such as impedance matching, radiation pattern, and gain. Modify the design parameters iteratively to achieve the desired electrical performance based on simulation results. Using High Frequency EM simulation tool surface current distribution is a one of analytical methods to optimize the microstrip patch antenna using above mentioned EM simulation tool like HFSS and CST etc.

Fabrication Considerations:

Consider the fabrication technique suitable for the chosen substrate and patch antenna design, such as PCB manufacturing or microstrip technology. Determine the manufacturing tolerances and capabilities of the chosen fabrication method. Ensure that the selected substrate material and thickness are compatible with the fabrication process. Consult with manufacturers or fabricators to confirm the feasibility of the chosen design and fabrication approach.

Wet Etching Method:

I. **Etching:**

Immerse the substrate with the patterned photoresist in an etchant solution that selectively removes the exposed areas of the substrate. The etchant used depends on the substrate material, but common etchants for FR4 and RT/Duroid include ammonium persulfate (APS) or ferric chloride (FeCl3). Monitor the etching process to ascertain the intended depth and accuracy are attained. Rinse the substrate thoroughly after etching to remove any residual etchant. Remove the remaining photoresist from the substrate using a suitable resist stripping agent, such as acetone or a specialized resist stripper.

Another method of fabrication is using a PCB machine e.g. EP2006H in which once the design has been sensed no need to manually adjust the PCB. Machine automatically provide the etching process and depth that is required to fabricate the antenna.

Figure 1: PCB prototyping Machine

II. Prototyping and Testing:

A physical prototype of the patch antenna will be assembled employing the selected substrate material., dimensions, and fabrication method. Validate the antenna's performance through measurement and testing. Characterize key parameters, including bandwidth, return loss, gain, and radiation pattern. Compare the measured outcomes with the simulation data to assess the prototype's adherence to the design specifications. If necessary, refine the design and fabrication process based on the testing results.

III. Anechoic Chamber:

While anechoic chambers represent the prevalent standard for antenna characterization, particularly within the microwave and millimetre-wave regimes, their adoption involves significant infrastructural investment. These devices have the advantages of a controlled electromagnetic environment and are much simpler to operate. Commonly, the chamber is a large shielded room lined with steel plate to prevent interference from external broadcasting. In addition, the internal surfaces are coated with pyramidal radio frequency absorbers, reducing signal reflection and simulating free space propagation, seen in Figure 2.

Figure 2: Anechoic chamber for antenna parameter measurement

IV. Iterative Refinement and Optimization:

The field test results would be used to evaluate potential deviations or sub-optimal attributes of the manufactured rectangular antenna. If you can identify any bad factor such as, impedance matching, radiation efficiency or bandwidth, the reason should be closely studied. Further cycles of fabrication and testing are suggested in order to satisfy the target specifications.

9. Tentative Structure/Chapter Outline of the thesis:

This dissertation conducts an in-depth study focused on the design, analysis, and performance improvement of flexible planar antennas intended for the Industrial, Scientific, and Medical (ISM) frequency bands. Structured across five comprehensive chapters, the work systematically explores this critical area within contemporary antenna engineering.

The **Chapter One** outlines the research context, clearly stating the main objectives and motivations for investigating flexible antenna systems. It situates the study within the broader landscape of modern applications and addresses the persistent challenges and limitations found in current flexible antenna designs for the ISM band.

Chapter Two delves into foundational aspects of microstrip planar antenna theory, covering essential operating principles and core characteristics. The literature review in this section synthesizes major developments and highlights current research directions within the field of flexible antennas. The chapter concludes with an analytical discussion of key performance parameters and compares various feeding techniques pertinent to planar antenna design.

Chapter Three delves into the methodological core of the thesis. It provides a rigorous exposition of the key performance metrics for flexible antennas. This chapter is pivotal, as it

presents a detailed parametrical analysis, investigating the profound effect of various structural and material properties on the antenna's operational characteristics, thereby guiding the subsequent design process.

Chapter Four constitutes the primary research contribution of this work. It introduces the practical design, simulation, and analysis of novel flexible planar antenna structures optimized for the desired ISM band. A significant focus is placed on implementing and evaluating innovative techniques for bandwidth broadening and gain enhancement, demonstrating a concerted effort to overcome performance limitations and advance the state-of-the-art.

Chapter Five synthesizes the entire research endeavour by summarizing the principal conclusions drawn from the findings. It reflects on the achievement of the initial research objectives and, looking forward, proposes several exploratory avenues and compelling ideas for future work in the dynamic field of flexible antenna design.

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